A Simplified Probabilistic Safety Assessment of a Steam-Methane Reforming Hydrogen Production Plant coupled to a High-Temperature Gas Cooled Nuclear Reactor

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Abstract – *A Probabilistic Safety Assessment (PSA) is being developed for a steam-methane reforming hydrogen production plant linked to a High-Temperature Gas Cooled Nuclear Reactor (HTGR). This work is based on the Japan Atomic Energy Research Institute's (JAERI) High Temperature Test Reactor (HTTR) prototype in Japan. This study has two major objectives: calculate the risk to onsite and offsite individuals, and calculate the frequency of different types of damage to the complex. A simplified HAZOP study was performed to identify initiating events, based on existing studies. The initiating events presented here are methane pipe break, helium pipe break, and PPWC heat exchanger pipe break. Generic data was used for the fault tree analysis and the initiating event frequency. Saphire was used for the PSA analysis. The results show that the average frequency of an accident at this complex is 2.5E-06, which is divided into the various end states. The dominant sequences result in graphite oxidation which does not pose a health risk to the population. The dominant sequences that could affect the population are those that result in a methane explosion and occur 6.6E-8/year, while the other sequences are much less frequent. The health risk presents itself if there are people in the vicinity who could be affected by the explosion. This analysis also demonstrates that an accident in one of the plants has little effect on the other. This is true given the design base distance between the plants, the fact that the reactor is underground, as well as other safety characteristics of the HTGR. Sensitivity studies are being performed in order to determine where additional and improved data is needed.*

I. INTRODUCTION

The Japanese Atomic Energy Research Institute (JAERI) is currently building a hydrogen production plant, that uses the methane reforming method and its thermal energy is provided by a nuclear High Temperature Test Reactor (HTTR). Information was gathered from publicly available documents in order to describe the systems and their components of the HTTR [1] and P&IDs of the plant [2]. Generic failure rates were used in the analysis. The chemical plant failure rates are taken from *Guidelines for Process Equipment Reliability Data with Data Tables*, [3], and the nuclear component failure rates from the PRA Procedure's Guide [4] and a study on operational experience at Fort St. Vrain [5] .

In a previous study, various initiating events and their, possible consequences were identified [6]; with this information event trees were constructed for three initiating events that could most impact public health. The objective of this paper is to present possible accident sequences and their frequencies, with more emphasis placed on the economic risk of the chemical plant and the fact that it is coupled to an HTTR. With the event trees, it is possible to define different end states and not all result in explosion. With this information it was possible to determine the components that contribute most to the accidents and perform various sensitivity studies in order to determine how to reduce the frequency of the events.

II. Description of the Complex

It is necessary to fully understand the design of the plants that constitute the complex and their safety systems in order to be able to develop the event trees and reflect in them the chronology of the actuation of the mitigating systems. Complete knowledge about the components of the safety systems is also crucial to the development of the fault trees and data base. Given the limited information available, assumptions were made when necessary and are indicated as such throughout the paper.

II.A. Main HTTR Systems

One of the main characteristics of HTTR safety is the fuel design, which consists of coated fuel particles (CFP's) that should not fail during normal operation and anticipated operational occurrences (AOO's). Among the safety characteristics of the reactor are the following: the maximum fuel temperature does not exceed 1600°C in any AOO. The reactor will be shut down in a safe and reliable way during operation using a control rod system. In addition, the Reserve Shutdown System (RSS) is independent of the control rod system. Another system is designed to remove decay heat after reactor shutdown for any AOO or accident. The HTTR has a containment vessel to prevent a release of fission products (FP's) and an excessive ingress of air in the case of a depressurization accident. The pressure in the Pressurized Water Cooling System (PWCS) will be controlled and will have less pressure than that of the primary helium to prevent a large ingress of water into the core in case of a heat exchanger tube rupture in the Pressurized Primary Water Cooler (PPWC). The pressure of the helium in the Secondary Helium Cooling System (SHCS) will be slightly higher than the primary to prevent release of fission products, from the Primary Cooling System (PCS) to the secondary, through a break in the heat exchanger (IHX) pipe.

II.B. Description of the Chemical Plant
II.B.1. Description of the Methane Reforming Process.

The most efficient and economic way to generate hydrogen is by the methane reforming process, although the use of this method generates carbon dioxide, the production of this greenhouse gas is reduced by almost 22% [6] when using a nuclear reactor as the heat source. The methane reforming method consists of breaking the link between the carbon and the hydrogen in the methane, with the help of heat and water vapor, this causes the carbon to oxidize generating carbon dioxide and hydrogen.

The methane reforming process is the following: natural gas is injected and passes through a desulfurizer to reduce the production of SOx, once reduced the level of sulfur in the natural gas, it is mixed with superheated water vapor and enters the reformer where carbon monoxide and hydrogen are produced. More water is added to the resulting mixture to generate more hydrogen and generate carbon dioxide, which is less contaminating than carbon monoxide; this reaction takes place in a *shift reactor*. The process is shown in Figure 4.

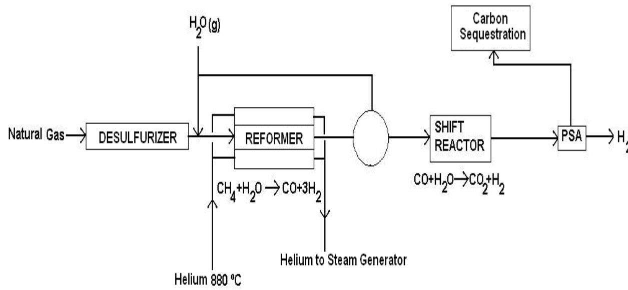

Fig. 4

A diagram was constructed on the basis of available information about the coupling of the HTTR and the steam methane reforming plant

III. ACCIDENT SEQUENCES

With help from HAZOP several events were chosen which were deemed as possible to lead to public health effects. [6] The initiating events were postulated in the reactor as well as in the chemical plant. Three of the events chosen were rupture in the methane piping, helium pipe rupture and rupture in the primary heat exchanger. These failures were postulated in the worst place in order to cause the largest damage, without losing the objectivity of the analysis. The Monte Carlo method which is integrated in SAPHIRE [7] was used for the uncertainty analysis.

III.A. Methane Pipe Rupture (RU-ME).

A value of 2.35E-4/año [3] was used for the initiating event frequency; this event was chosen due to the fact that methane is potentially explosive and could cause substantial damage to onsite personnel as well as to the general public.

The event considered is a total break in the methane piping in the place that would cause the most damage and with the least possibility of preventing the explosion. There is a nominal flow of 1400Kg/h that leaks from the pipe; the only way to stop the flow is by stopping the pump BM01 (see Figure 6).

III.A.1. Location and Description of the Break.

In this event there is a rupture in the methane pipe as shown in Figure 6; it is located between the evaporator EM01 and the pressure control valve VCPM02. When a pressure difference is detected, a signal is sent to stop the pump BM01, while all the helium from the reactor is sent to the PPWC. If for some reason the flow cannot be

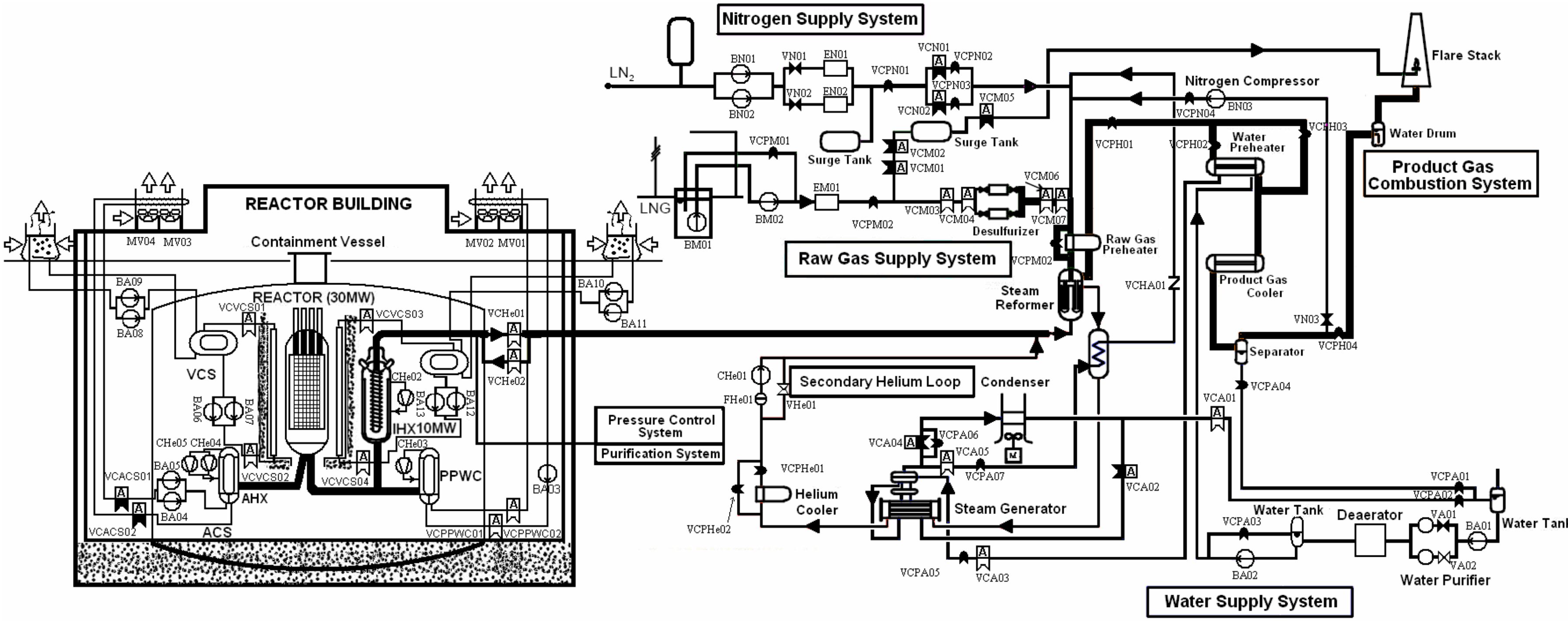

Fig. 5 Coupling of HTTR and Methane Reforming Plant

diverted or a SCRAM must be initiated, the PPWC is designed to dissipate the 30 MW from the reactor.
If there is a SCRAM, the MCS stops and the ACS and the VCS start, which remove the decay heat from the reactor.

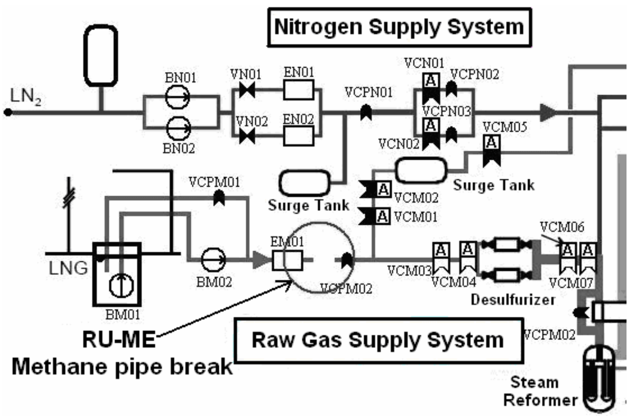

Fig 6. Location of Methane Pipe Break.

III.A.2. Results for the Initiating Event RU-ME.

Figure 7 presents the event tree that was built for this initiating event using the computer program, SAPHIRE, developed by the INEEL[7].

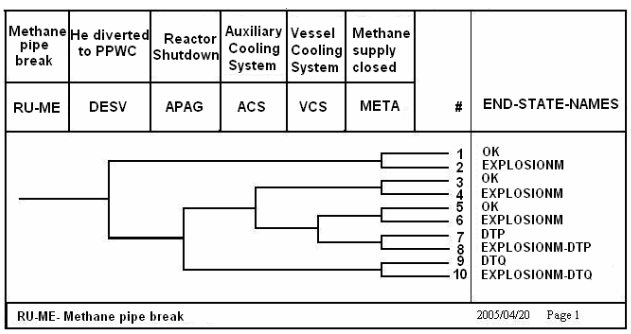

Fig 7. Event Tree for the initiating event RU-ME.

Table I presents the definition of the possible end states for the event tree presented in Figure 6. Although the last two of the end states do not cause health effects, they are considered due to the economic effect that they imply due to plant damage.

TABLE I. End States for Initiating Event RU-ME

EXPLOSIONM[1]	The methane supply is not closed
DTP	Partial thermal damage to the reactor due to the fact that the reactor was shutdown but no cooling was available.
DTQ	Thermal damage to the chemical plant, in particular where the helium of the secondary circuit is in contact with the reformer; given that there is no methane flow, the reformer pipes heat up.

[1] The quantity of gas accumulated will depend on the time to repair the pump BM01, 10 minutes were calculated to be able to accumulate 233.33Kg of methane, if it were to burn it could cause second degree burns after 20 seconds of exposition to people located 100 meters from the center of the fire.

Fault trees were constructed to be able to calculate the frequencies of the sequences, one for each mitigating system shown in the headings of the event trees. The level of detail in the fault trees reached the components, considering their power supply as the support system; other support systems were not considered due to the lack of detailed enough information. The failure of the power supply as an initiating event will be analyzed in a future study.

The fault trees are not presented in this paper, they can be found in the report [8]. The fault trees were built and quantified with SAPHIRE also. The failure rates for each component were obtained from various references, including the PRA Procedures Guide [4] and the Guide for reliability data in the process industry [3]. Data for the failure of the operator to shut down the reactor and the failure of the insertion of the control rods were taken from the report on the operational experience in Fort St. Vrain, a High Temperature Gas Cooled reactor that operated in the United Status for ten years [5].

Once evaluated the fault trees, the probability of failure of each system was calculated; Table II shows the results of the failure probability for each system involved in the event tree for the initiating event RU-ME.

TABLE II. System Failure Probabilities for RU-ME

System	Failure Probability
VCS	9.84×10^{-3}
ACS	6.59×10^{-3}
DESV	2.54 x 10-4
META	2.53 x 10-4
APAG	5.10 x 10-6

Once the fault trees were evaluated, the frequencies of the accident sequences were quantified. The sequences were grouped by end states in order to evaluate the frequencies of the possible consequences for this event. The results for all the end states considered in this paper are shown in Table V. In particular, the results for this event tree show a mean frequency of 6.53×10^{-8} for a methane explosion, 2.60×10^{-7} for DTP, and 3.15×10^{-13} for DTQ.

III.B. Helium Pipe Rupture (RU-HE)

This event is considered the worst event by the HTTR designers, and is referred to as a depressurization accident. It consists of a total rupture of the coaxial pipe that goes to the PPWC and the heat exchanger (IHX). This break could cause the coolant to leave the pressurized vessel and leave the reactor without coolant, in Duch a way that the ACS would not be available and the only way to remove the dacay heat is with the VCS.

III.B.1. Location and Description of the Helium Pipe Break.

A frequency of 2.12E-5/year is considered for this large break [7] and it is localized in the outlet of the pressurized vessel, as illustrated in Figure 9. When the pressure difference is detected, a SCRAM occurs, the coolant is released to the containment. The containment isolation valves must close to avoid liberation of fission products, although a small quantity may leak to the atmosphere through the service area due to the increase in the containment pressure. The ACS cannot operate under these conditions to prevent the entrance of air into the core. The decay heat is removed by radiation by the VCS. When the pressure inside the core and the mixture of helium/air is the same, air may enter by natural convection and oxidize the graphite structures until the VCS cools the reactor and the oxidation reaction stops.

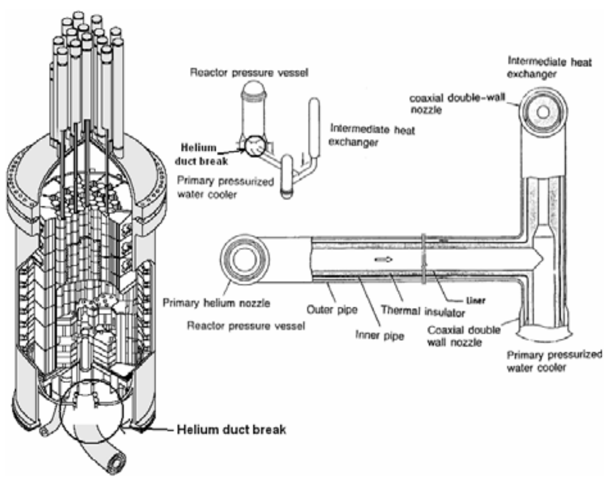

Fig 9. Location of the Helium Pipe Break RU-HE.

III.B.2. Results for Helium Pipe Rupture RU-HE.

By failing the mitigating systems that could enter to avoid possible accident consequences, it was possible to create the event tree presented in Figure 10. The system entitled CV_VALVE, the containment isolation valve, avoids the liberation of fission products out of the vessel containment. The end states for this initiating event are shown in Table III.

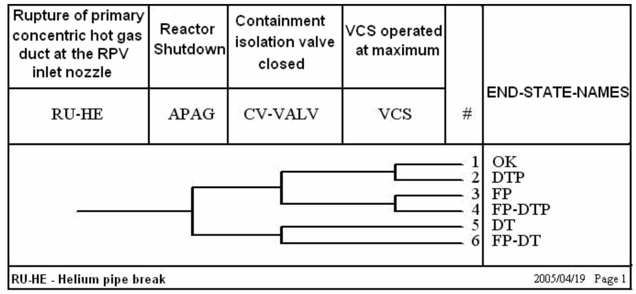

Fig 10. Event Tree for the Initiating Event RU-HE.

TABLE III. End States for Helium Pipe Break

DTP	Partial thermal damage, given that the reactor is shut down, the reactor is will be cooled by natural convestion.
FP	Fission Product release through the service area.
DT	Thermal damage, the reactor was not shut down, por lo tanto, no se activa el VCS,

*El daño se debe sobre todo al encamisado del combustible y es parcial debido a que se logra a pagar el reactor pero se enfría por convección natural, debido a que ningún sistema de enfriamiento logró entrar.
**Las fuentes de FP consideradas en el análisis son: FP contenidos en el refrigerante primario, FP que cubren la superficie interna del sistema primario de enfriamiento y FP contenidos en el núcleo (combustible) los cuales son liberados adicionalmente durante el accidente.
***El diseño del reactor HTTR tiene una retroalimentación negativa debido al efecto Doppler del combustible, logrando alcanzar 1600ºC como temperatura máxima.

The probabilities for the systems are shown in TABLE V.

TABLE V. System Failure Probabilities

System	Failure Probability
VCS	9.84×10^{-3}
AGUA-PPWC	4.47×10^{-3}
CV-VALV	2.83×10^{-4}
APAG	5.10×10^{-6}

The system CV-VALV is responsible for the closure of the isolation valve to avoid fision product release. Since the frequency of this initiating event is $2.12\text{x}10^{-5}$/year[2], even if the probability of failure of CV-VALV were large,

[2] This value is conservative since the value for a large LOCA was assumed, given no data was found for breaks of concentric pipes.

the end state is for FP is 6 x 10^{-9}/year, as can be seen in Table VI.

II.C. Rupture of a pipe in the PPWC (RU-PPWC).

This initiating event is assumed to have a frequency of 5E-4/year [4] and is considered important because if a large amount of water were to enter into the reactor, first there is a probability that the internal graphite structures could be oxidized and if the reactor is not shut down, hydrogen would be produced in the core, possibly resulting in an explosion.

III.C.1. Location and Description of the Event RU-PPWC.

In the case of a break in a heat exchanger pipe inside the PPWC (see Figure 11), the pressurized water could enter into the primary helium loop and if so would evaporate given the heat of the structures in the reactor. The water that enters inside the core would cause oxidation of the graphite, as well as increase the reactivity. A SCRAM occurs when the a decrease is detected in the pressure between the primary helium gas and the pressurized water. Simultaneously, the PPWC is isolated from the water pump by closing an isolation valve to prevent an even greater ingress of water into the reactor core.

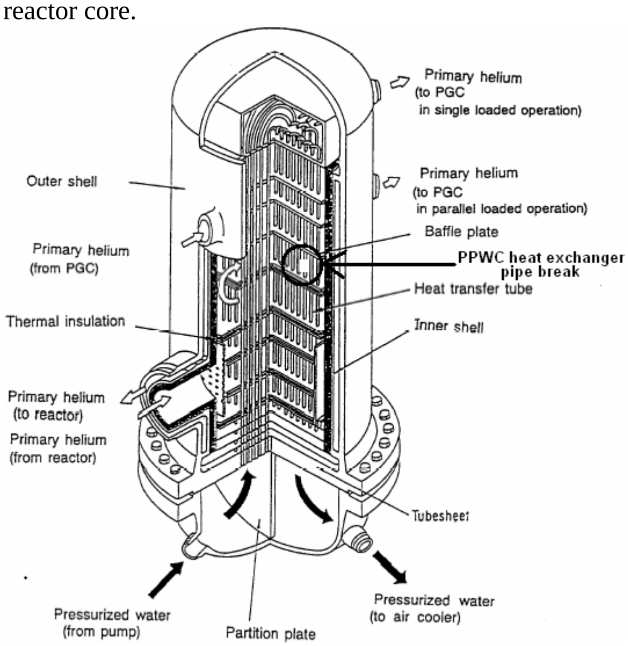

Fig 11. Location of the break RU-PPWC.

III.C.2. Results for the Event RU-PPWC.

The Event Tree was developed for the PPWC heat exchanger pipe break and is presented in the Figure 12, and the end states are shown in Table V.

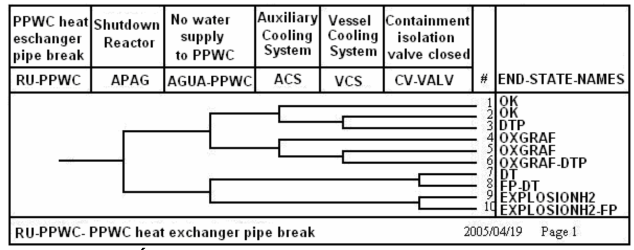

Figura 12. Árbol de eventos para el evento iniciador RU-PPWC

TABLE V. End States for RU-PPWC

DTP	Partial thermal damage to the reactor due to the fact that the reactor was shutdown but no cooling was available.
OXGRAF	This refers to the oxidation of the graphite given the ingress of water into the reactor.
EXPLOSIONH2	Given the accumulation of
EXPLOSIONH2-FP	

IV. General Results

Table I shows the failure probability of each system and Table II shows the frequency of each end state in descending order. The point value, mean, 5% and 95% values are shown here as calculated in the ucertainty analysis.

TABLE I. Probability of System Failure.

Fault Tree Review - (HTTR-H2)

Fault Tree	Frequency	Mean	5th	Median	95th
VCS	1.015E-02	9.843E-03	4.579E-03	8.872E-03	1.847E-02
ACS	8.452E-03	6.587E-03	1.974E-03	4.982E-03	1.523E-02
AGUA-PPWC	4.672E-03	4.470E-03	1.285E-03	3.352E-03	1.155E-02
CV-VALV	2.828E-04	2.752E-04	1.781E-05	1.466E-04	8.813E-04
DESV	2.780E-04	2.538E-04	1.345E-05	1.183E-04	9.473E-04
META	2.780E-04	2.538E-04	1.345E-05	1.183E-04	9.473E-04
APAG	4.816E-06	5.096E-06	4.158E-07	2.335E-06	1.951E-05

TABLE II. End State Frequency .

EndState Review - (HTTR-H2)

End State	Frequency	Mean	5th	Median	95th
OXGRAF	2.336E-06	2.215E-06	6.559E-07	1.773E-06	5.206E-06
DTP	2.596E-07	2.468E-07	1.112E-07	2.155E-07	4.821E-07
EXPLOSIONM	6.533E-08	6.580E-08	3.473E-09	2.762E-08	2.300E-07
FP	5.996E-09	5.571E-09	3.878E-10	2.788E-09	2.039E-08
DT	2.510E-09	2.410E-09	2.330E-10	1.171E-09	8.295E-09
OXGRAF-DTP	2.082E-10	1.782E-10	2.127E-11	9.977E-11	5.335E-10
FP-DTP	6.108E-11	5.775E-11	3.237E-12	2.463E-11	1.929E-10
EXPLOSIONH2	1.127E-11	1.120E-11	4.849E-13	4.153E-12	4.558E-11
FP-DT	7.100E-13	8.922E-13	1.237E-14	1.707E-13	2.916E-12
DTQ	3.147E-13	3.248E-13	4.790E-15	7.313E-14	1.292E-12
EXPLOSIONH2-FP	3.186E-15	3.129E-15	2.748E-17	5.445E-16	1.423E-14
EXPLOSIONM-DTP	1.617E-15	1.706E-15	7.462E-18	1.790E-16	5.345E-15
EXPLOSIONM-DTQ	8.748E-17	8.782E-17	2.348E-19	8.114E-18	2.598E-16
TOTALS =	2.670E-06	2.536E-06			

From Table I we can observe that the system with the gratest failure probability is the VCS. Although the VCS has the largest failure probability, it is not the system that contributes most to the end state frequency. The system that contributes most is to an accident that affects health is the system META. The failure or success of the system VCS affects the economic study more than the health risk.

In Table II we can observe that the end state with the highest frequency is OXGRAF, which refers to the oxidation of the internal graphit structures in the reactor pressure vessel. Because this analysis focused in on public safety, for this reason only these events were analyzed; however, more events are to be analyzed in future work to provide a more solid basis for design modifications.

Observing Table II we find three end states that provoke damage to the onsite, and possibly offsite, population: EXPLOSIONM, EXPLOSIONH2, FP and these same ocurrences but with different extensions added, such as DT, DTP, DTQ.

TABLE III Frequency of End States that Affect Health

EndState Review - (HTTR-H2)

End State	Frequency	Mean	5th	Median	95th
EXPLOSIONM	6.533E-08	6.420E-08	3.620E-09	3.198E-08	2.194E-07
FP	5.996E-09	5.634E-09	3.821E-10	2.561E-09	1.993E-08
FP-DTP	6.108E-11	6.609E-11	3.329E-12	2.602E-11	2.393E-10
EXPLOSIONH2	1.127E-11	1.208E-11	5.289E-13	4.126E-12	4.400E-11
FP-DT	7.100E-13	6.887E-13	9.135E-15	1.534E-13	2.747E-12
EXPLOSIONH2-FP	3.186E-15	2.802E-15	2.798E-17	5.952E-16	1.143E-14
EXPLOSIONM-DTP	1.617E-15	1.351E-15	8.714E-18	2.044E-16	5.143E-15
EXPLOSIONM-DTQ	8.748E-17	1.170E-16	2.870E-19	9.393E-18	3.048E-16
TOTALS =	7.140E-08	6.991E-08	4.003E-09	3.457E-08	2.396E-07

Table III shows only the end states that could have an effect on the population in terms of death and injury. The mean frequency is 6.991E-8/año.

V. IMPORTANCE AND SENSITIVITY STUDIES

The mean frequency of this end state is 6.6E-8/year, if it were necessary to reduce this frequency, it is possible to rank the importance of the components that are involved in these sequences. It was found that the methane pump BM01 contributes most to this frequency, since the failure to stop this pump results in an accumulation of methane at the place of the break. Given the design[3], there is no way to stop the methane flow if the pump is not stopped. For this reason, several modifications were suggested to study their impact on the end state frequency. One suggestion was to place a cutoff valve before the evaporator, shown as VCM-A in Figure 7. The other was to observe the failure probability of the pump necessary to achieve a risk reduction comparable to that achieved with the addition of the new valve.

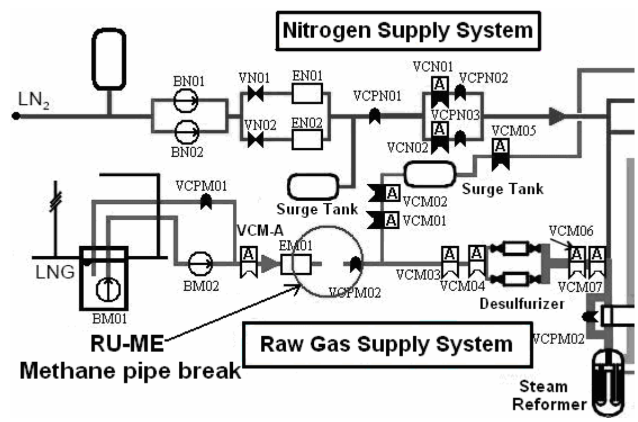

Fig. 7. Cutoff valve VCM-A added to design

The results show that the new cutoff valve reduces the end state frequency from 6.5E-8/year to 1.4E-10/year. In order to achieve this same reduction in frequency of the methane explosion end state, it would be necessary to decrease the failure probability of the pump from 2.78E-4 to 6E-7, which falls outside the 90% range of certainty considered in this study.

VI. CONCLUSIONS

In general the system with the largest failure probability is VCS with a mean value of 9.8×10^{-3}. The system with the lowest failure probability is the shutdown system, APAG, with a mean value of 5×10^{-6}.

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[3] We must iterate that this reflects the results based on the design presented here, and may not reflect the real design.

The end state with the largest frequency is graphite oxidation with a mean value of 2.20 x 10^{-6}/año; although this was the end state with the largest frequency and contributes % to the total accident frequency, it is a small frequency when compared to the frequency of core melt of a BWR, in the range of 10^{-6} to 10^{-5}/year.

This end state affects the economic part of the damage and will be used to do future analysis for definig design changes. The frequency of events that would have an affect on the population, onsite and possible offsite 4E-9/año a 2.4E-7/año; where the most frequent end state is the methane explosion 3.806E-9/año a 2.475E-7/año. The next most frequent end state is that of fission product release with a mean value of 4.056E-10/año a 2.095E-8 and finally the least frequent is that involving the hydrogen explosion in the reactor vessel with a mean value of 5.541E-13/año a 4.268E-11/año.

Although generic failure rates were employed, and when the data did not exist, conservative values were used, the end state frequencies were small. Although the the analysis is simplified, if other factors were to be considered, such as taking credit for human actions, component repair, etc, further reduction in frequencies would be expected. More plant specifc data and or data with less uncertainty could help to refine the analysis.

Future work includes more sensitivity studies in order to determine the impact of possible modifications in the design and operation of the plant. For example, sensitivity tests could be done on the first event, which resulted in the dominant frequncy, that is, calculate the risk reduction by adding a cutoff valve in the methane pipe. If the sensitivity study results in important risk reduction, the next step is to evaluate the cost of the modification and present the cost/benefit or value/impact results as a piece of information important to consider in the decision making process.

Another part of future work involves considering the initiating event, loss of offsite power, dominant in BWRs, but is proving to be much less so in HTGRs..

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